

# Gluon radiation by heavy quarks at intermediate energies and consequences for the mass hierarchy of energy loss

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## Abstract

We extend the Gunion Bertsch calculation of gluon radiation in single scattering to the case of finite mass quarks. This case applies to the radiative energy-loss of heavy quarks of intermediate energies propagating in a quark gluon plasma. We discuss more specifically the dead cone effect as well as the mass hierarchy of the collisional and radiative energy loss and provide some predictions for observables sensitive to the mass hierarchy of energy loss in ultrarelativistic heavy ion collisions.

**Keywords:** heavy quarks, gluon radiation, energy loss, quark gluon plasma

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## 1. Introduction

The quenching of heavy quarks (HQ) produced in the initial stage of ultrarelativistic heavy ion collisions is generally accepted as a good probe of the quark-gluon plasma created in those collisions. Among other interesting features, one usually quotes the mass hierarchy expected in the energy loss and thermalization processes, which offers a different perspective as compared to the quenching of light particles. This mass hierarchy is often discussed intricately with the dead cone effect which reduces the gluon bremsstrahlung in HQ production and could affect the *induced* radiation in QGP as well [1]. One goal of this contribution is to show that, strictly speaking, the dead cone effect is not the main contributor to the mass hierarchy found in radiative energy-loss. For this purpose, we rely on our recent calculation of the radiative energy-loss of heavy quarks at intermediate energies [2], summarized in section 2. In such a regime, the typical invariant square mass  $s$  of collisions with the QGP constituents is not  $\gg m_Q^2$  and the coherence effects are not expected to dominate the physics, but rather the phase space boundaries. We have therefore advocated in [2] that extending the calculation of Gunion and Bertsch (GB) [3] to finite quark-mass could offer a valid alternative perspective to the "high energy approach" [4], especially for the case of identified open-beauty mesons produced in AA collisions.

Another goal of this contribution is to remind the reader that the mass hierarchy found in radiative energy loss is also inherent to collisional energy-loss, as shown in section 3 where various models are compared. This implies that recent experimental evidence of such mass hierarchy in heavy-flavour quenching [5] has to be considered with care before precise conclusions can be drawn on its origin. In order to contribute to this topic, we have implemented, in section 4, different energy-loss models in our dynamical MC@,HQ+EPOS2 simulator [6] and in order to make predictions for observables sensitive to their mass dependence.

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## 2. Radiative energy loss at intermediate energy

We summarize the main points of [2], in which the reader can find further details and explanations. For intermediate energies, coherence effects can be neglected and the dominant contribution to the radiated gluon stems from a gauge-invariant ensemble of diagrams, including the one where the radiated gluon is attached to the gluon exchanged between the light parton (of 4-momentum  $q$ ) and the HQ (of 4-momentum  $P$ ). A compact and exact expression is found for the dominant part of the radiation probability:

$$\frac{d\sigma^{Qq \rightarrow Qqg}}{dx d^2k_t d^2l_t} = \frac{\Theta(\Delta)}{8(2\pi)^5 (s - m_Q^2) \sqrt{\Delta}} \left| g C_3 \left( \frac{-4g^2 P \cdot q}{\ell^2} \right) \left( \frac{(2(1-x) - x') \vec{\epsilon}_t \cdot \vec{k}_t}{\vec{k}_t^2 + x^2 m_Q^2} - \frac{2(1-x-x') \vec{\epsilon}_t \cdot (\vec{k}_t - \vec{l}_t)}{(\vec{k}_t - \vec{l}_t)^2 + (x+x')^2 m_Q^2} \right) \right|^2, \quad (1)$$

where  $\vec{k}_t$  and  $\vec{l}_t$  are respectively the transverse momentum of the radiated and of the exchanged gluons (with respect to the incoming HQ direction),  $x$  is the fraction of  $P$  carried away by the gluon (after Sudakoff decomposition) and  $\Delta$  represents the phase space. When  $k_t^2, l_t^2 \ll x(s - m_Q^2)$ , eq. (1) simplifies and one recovers the "high energy limit":

$$\frac{d\sigma^{Qq \rightarrow Qqg}}{dx d^2k_t d^2l_t} = \frac{d\sigma_{\text{el}}}{d^2l_t} P_g(x, \vec{k}_t, \vec{l}_t) \quad \text{with} \quad P_g = \frac{C_A \alpha_s}{\pi^2} \left( \frac{\vec{k}_t^2}{k_t^2 + x^2 m_Q^2} - \frac{(\vec{k}_t - \vec{l}_t)^2}{(\vec{k}_t - \vec{l}_t)^2 + x^2 m_Q^2} \right)^2, \quad (2)$$

There exists 2 clear-cut regimes: In the "hard scattering regime"  $l_t \gg x m_Q$  ( $\Leftrightarrow x \ll x_M = \frac{\mu}{m_Q}$ , where  $\mu$  is the IR regulator introduced in  $\frac{d\sigma_{\text{el}}}{d^2l_t}$ ), one has  $P_g \approx \left( \frac{k_t^2}{k_t^2 + x^2 m_Q^2} \right)^2$ , which is the usual dead cone effect advocated in [1]. In the "soft scattering regime"  $l_t \ll x m_Q$ , both terms in  $P_g$  interfere and the dead cone in  $k_t$  space is replaced by a plateau of height  $P_g \propto \frac{l_t^2}{(x m_Q)^4}$ . This effect has first been shown in [7].

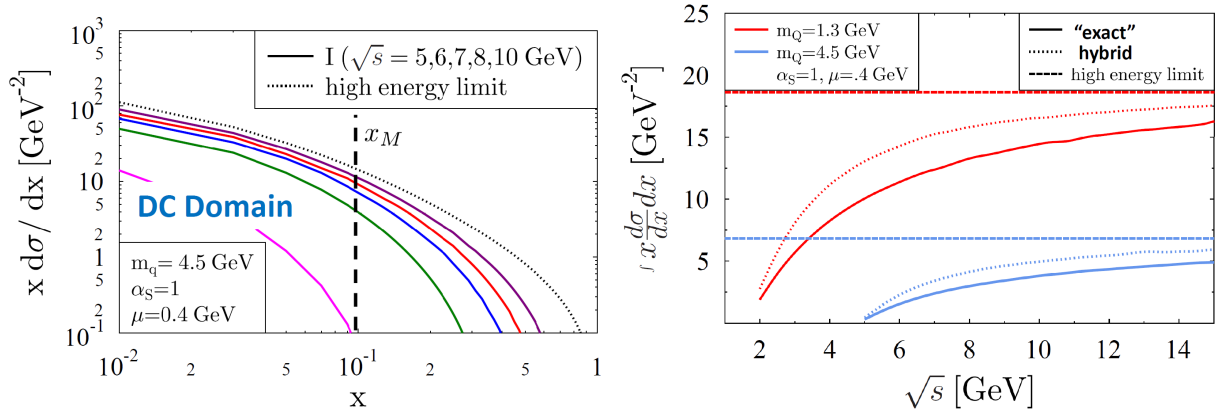


Figure 1. Left: the gluon emission cross section  $x \frac{d\sigma}{dx}$  in a  $b$ - $q$  radiative collision. Right: the moment  $\int x \frac{d\sigma}{dx} dx$ .

In fig. 1 (left), we display the gluon emission cross section for realistic values of  $\sqrt{s}$  in a collision between a  $b$ -quark of 10 GeV/c and partons of a  $T = 0.4$  GeV QGP, as well as for the HE limit (2) which constitutes an upper value. On the right panel, we show the moment  $\mathcal{I} = \int x \frac{d\sigma}{dx} dx$  appearing in the average Eloss as  $\frac{dE_{\text{rad}}}{dz} = \mathcal{I} \rho E$ .  $\mathcal{I}$  is  $\sqrt{s}$ -independent in the HE limit but strongly reduced at intermediate energies. Moreover,  $\mathcal{I}$  scales  $\propto m_Q^{-1}$  when plotted as a function of  $\sqrt{s} - m_Q$ . On fig. 1 (right), we also show the result of the "hybrid" model obtained by combining the  $d\sigma$  in eq. (2) with an exact phase space boundary. This hybrid model already contains the main features of the exact results but is much more efficient for MC implementation. It was therefore chosen for our code, after including a gluon thermal mass  $m_g = 2T$  for the radiated gluon. We model coherence effects of the LPM type according to [8], which has an impact for  $p_T \gtrsim 10$  GeV/c only.

### 3. mass dependence of collisional and radiative energy loss models

We now discuss the mass dependence of several Eloss models implemented in MC@\_sHQ, including the ones discussed in section 2 (rad. GB and LPM). On fig. 2 (left), we show the  $\langle dP_T \rangle / dt$  for a  $c$ -quark in a  $T = 400$  MeV QGP. For each model, one has applied an additional factor  $K$  to the interaction cross sections in order to reproduce the  $R_{AA}$  of  $D$ -mesons for  $p_T = 10$  GeV/c in the most central Pb-Pb collisions at LHC  $\sqrt{s} = 2.76$  TeV [9].

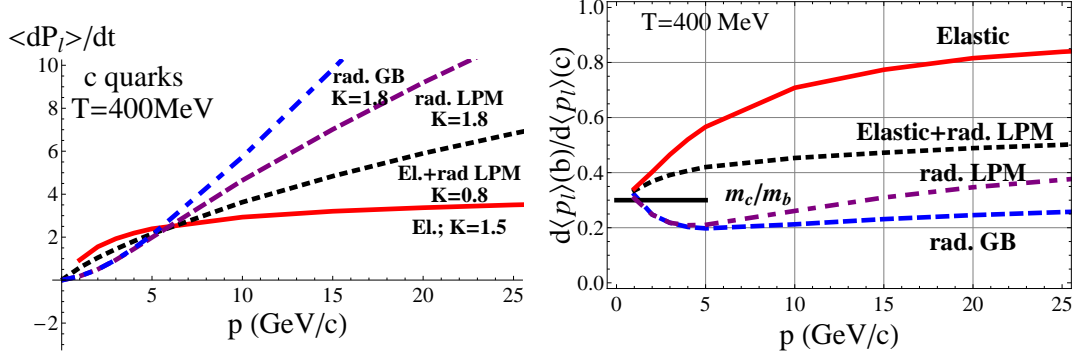


Figure 2. Left: average momentum loss for different models. Right: corresponding ratio of average momentum loss of  $b$ -quarks wrt  $c$ -quarks.

On fig. 2 (right), we show the ratio of the momentum loss of  $b$ -quarks as compared to the  $c$ -quarks, for the same energy-loss models. For small  $p$ , the ratio is close to  $m_c/m_b$ , confirming the generic nature of the mass hierarchy. With increasing  $p$ , mass hierarchy is the strongest for the radiative GB Eloss – in agreement with the  $m_Q^{-1}$  scaling mentioned previously – and tends to disappear from radiative Eloss once coherence effects are included, while the fastest disappearance of the mass hierarchy is observed for collisional Eloss.

### 4. Consequences for heavy ion collisions

We now investigate the consequences of the mass hierarchy on some experimental observables. For this purpose, we implement these models in our EPOS+MC@\_sHQ code, described in [6]. We first concentrate, in fig. 3, on the comparison between the  $R_{AA}$  of  $D$ -mesons and non-prompt  $J/\psi$  stemming from  $B$ -mesons, as a function of  $N_{part}$ . Such comparison is known to be a good probe of the mass hierarchy [10].

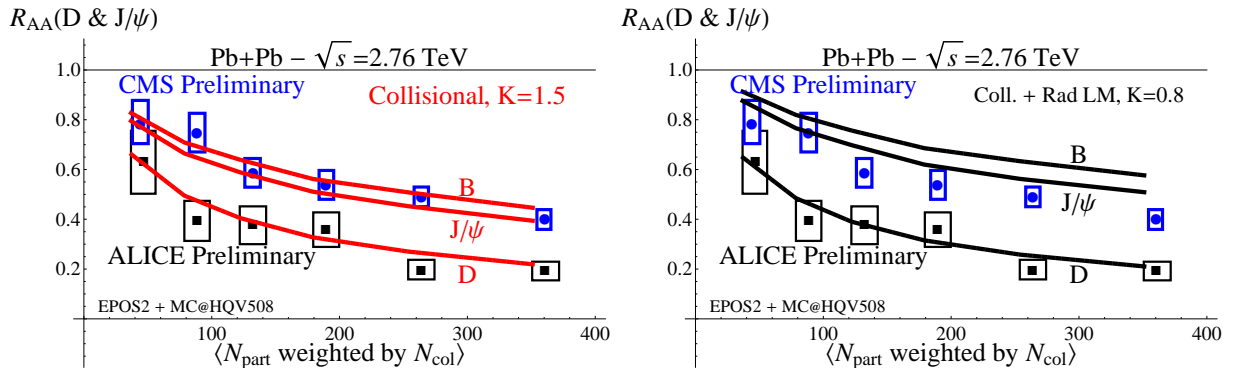


Figure 3.  $R_{AA}$  of  $D$  mesons,  $B$  mesons and non-prompt  $J/\psi$  daughters, as a function of the number of participants, for a purely collisional Eloss model (left) as well as for a collisional + radiative cocktail (right), compared with the preliminary data of ALICE [5] and CMS [11].

The actual experimental data are compatible with the mass hierarchy of both the pure collisional scenario as well as of the collisional and radiative LPM cocktail, with a slight preference for the first type of mass hierarchy (showing

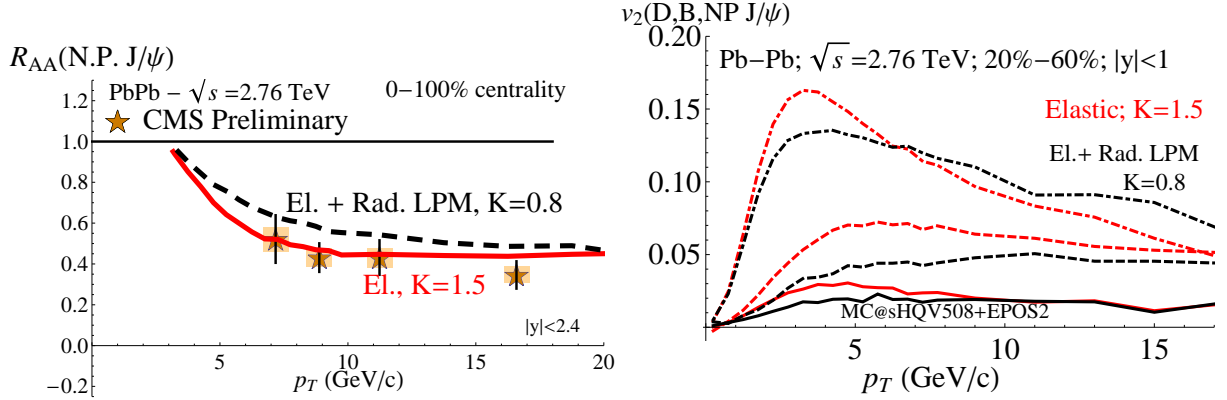


Figure 4. Left:  $R_{AA}$  of non-prompt  $J/\psi$  (decay product of  $B$ -mesons) for pure collisional Eloss model as well as for a collisional + radiative cocktail, as compared with CMS preliminary data. Right: prediction for the elliptic flow of  $D$  (dot-dashed),  $B$  (dashed) and non-prompt  $J/\psi$  mesons, using the same models.

the fastest disappearance with increasing momentum). Let us also mention that a) a pure radiative scenario is not able to cope with the combined  $D$ -mesons and non-prompt  $J/\psi$  data while b)  $b$ -quark evolution using the mass of  $c$ -quark leads to  $B$ -mesons  $R_{AA}$  close to those of the  $D$ -mesons. This demonstrates that the mass ordering observed in the  $R_{AA}$  is a genuine consequence of the mass hierarchy implemented in the models.

On fig. 4 (left), we display our prediction for the  $R_{AA}$  of non-prompt  $J/\psi$  vs  $p_T$  in unbiased Pb-Pb collisions at  $\sqrt{s} = 2.76$  TeV. The comparison with preliminary CMS data is acceptable for the 2 types of Eloss models. The elliptic flow ( $v_2$ ) of  $B$  mesons, shown in the right panel of fig. 4, appears to be sensitive to the mass hierarchy as well, but is reduced when measuring the  $v_2$  of the non-prompt  $J/\psi$  daughters.

## 5. Conclusions

We have contributed to the study of radiative energy loss by considering the case of heavy-quark at intermediate energies for which taking care of the phase space boundary appears to be a crucial issue. We have shown that our models of the HQ interactions with the QGP medium were compatible with the  $R_{AA}$  of  $D$ -mesons and  $B$ -mesons for all centrality classes in Pb-Pb collisions at LHC, while discrimination requires further improvement in the data. From this understanding, we were able to make a prediction for the  $v_2(B)$  which will be released soon by the CMS collaboration.

## 6. Acknowledgement

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